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A DESCRIPTION OF THE TURBOPROPULSION LABORATORY IN THE AERONAUTICS DEPARTMENT AT THE NAVAL POSTGRADUATE SCHOOL

Michael H. Vavra, et al

Naval Postgraduate School

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by

M. H. Vavra and R. P. Shreeve

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Michael H. Vavra
Raymond P. Shreeve

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13. ABSTRACT

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

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Academic Dean

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Extensive facilities have been developed at the Naval Postgraduate School for teaching and research in turbomachinery. In eight years of growth, more than 30 Naval officers have completed theses toward advanced engineering degrees. This report briefly describes the existing equipment and mentions examples of research both completed and underway. Particular details can be obtained from the listed references. The purpose of the report is to provide a convenient reference for present and prospective students and to satisfy inquiries from sources external to the School.

M. H. Vavra

M. H. Vavra
Distinguished Professor of Aeronautics

R. P. Shreeve

R. P. Shreeve
Visiting Associate Professor

Approved by:

R. W. Bell

R. W. Bell, Chairman
Department of Aeronautics

Released by:

John M. Wozencraft

J. M. Wozencraft
Dean of Research

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1. Introduction

The Turbo-Propulsion Laboratory was completed in 1964 under the supervision of the Bureau of Yards and Docks of the United States Navy. It is part of a complex which also contains rocket test cells, a supersonic blowdown wind tunnel and a low-speed oscillating flow wind tunnel. These facilities are housed in six buildings located close to the approach to Monterey airport, and their purpose is to serve the teaching and research needs of the Aeronautics Department of the Naval Postgraduate School.

The Turbo-Propulsion Laboratory uses three buildings of which one is a general purpose shop, one contains a cascade wind tunnel and a three stage axial research compressor, and the third is a fully equipped laboratory for turbine, compressor and model testing.

In this report, the facilities themselves are described and examples of recent research projects are given. The purpose of the report is to provide a convenient reference for new students, and to satisfy inquiries from sources external to the School. The report should be viewed as an outline rather than an exhaustive review of the work of the laboratory. Details of the equipment and research results are to be found in the references.

2. Cascade Wind Tunnel

The Cascade Wind Tunnel is an open cycle wind tunnel designed for investigating flows through rectilinear cascades of blades. A 750 H.P. fan produces Mach numbers up to 0.4 in a test section of 10 in. by 60 in. Figure 1 shows a schematic of the facility and figure 2 shows a view of the test section. Details of the installation and modifications that have been carried out are described in references 1-4.

The comparatively large scale of this facility allows the flow through cascades of turbine and compressor blade shapes to be investigated in detail. Semiautomatic traversing equipment and an electronic data acquisition system reduces the time taken to acquire and to reduce data.

Various types of multiple-hole pressure probes that measure local flow angle, pressure and velocity, and hot-wire anemometers are used after prior calibration in a known flow (Section 4). Surface flow visualization is obtained by lamp black and oil techniques, and tufts are also employed.

Two examples are cited of the type of work carried out using the Cascade Wind Tunnel. An investigation was made of the blading that was used in an actual turbine stage tested in the Turbine Test Rig (Section 4.3). Bartocci has reported this work in reference 3. In reference 4, Woods reports in a doctoral dissertation an investigation of the secondary flow losses in blading with very large turning angles. The span of fixed cascade was adjusted by means of side plates and detailed maps of the exit flow were obtained from probe surveys. After integration, it was possible to divide the losses into two-dimensional and secondary flow components. Examples of these results are given in figure 3. The latter work is part of a continuing program to evaluate secondary flow effects.

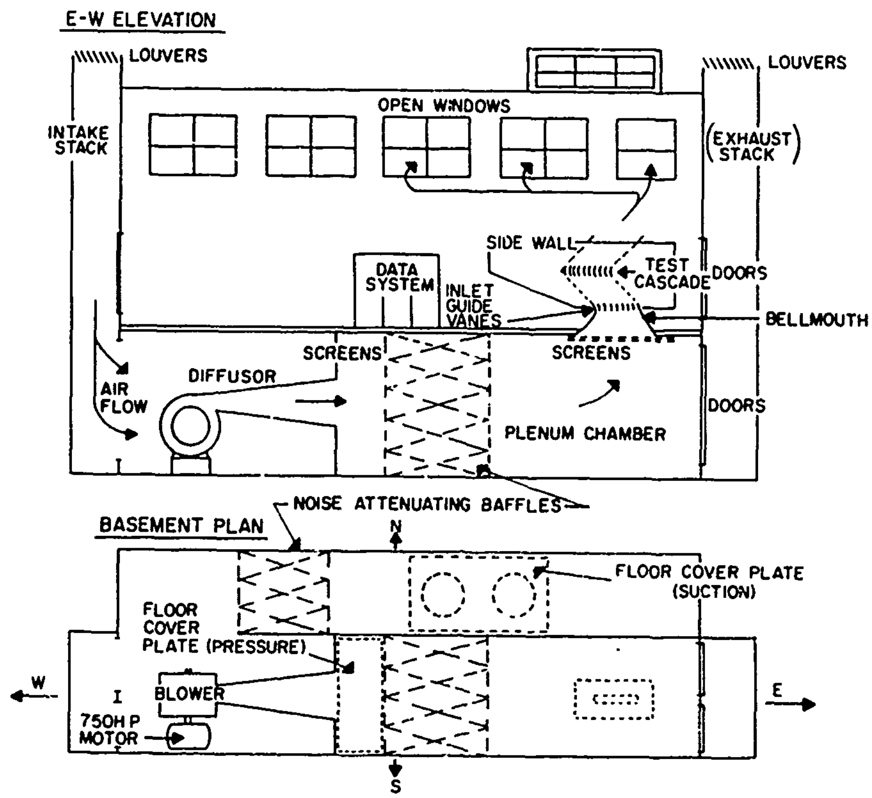


FIGURE 1: Schematic of the Cascade Wind Tunnel Facility

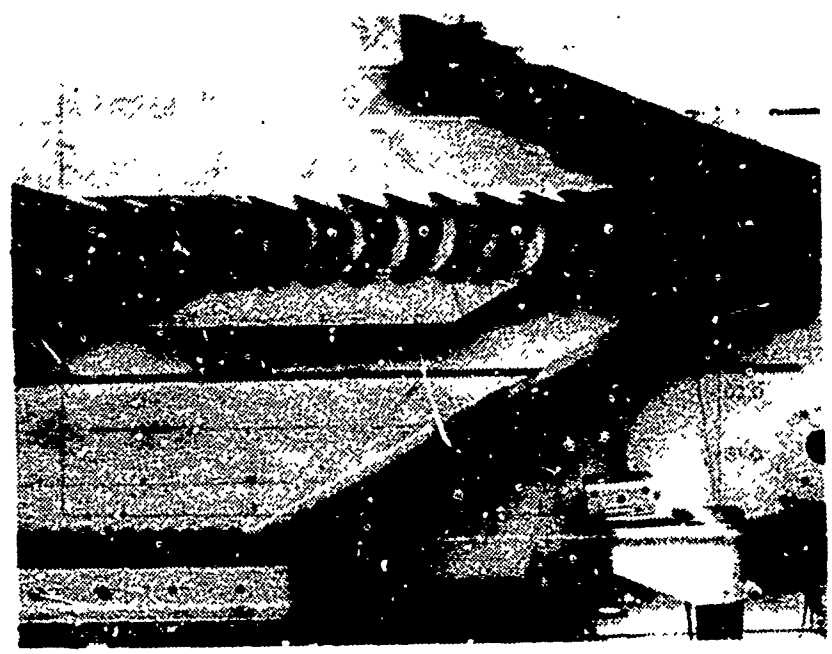


FIGURE 2: View of the Cascade Wind Tunnel Test Section

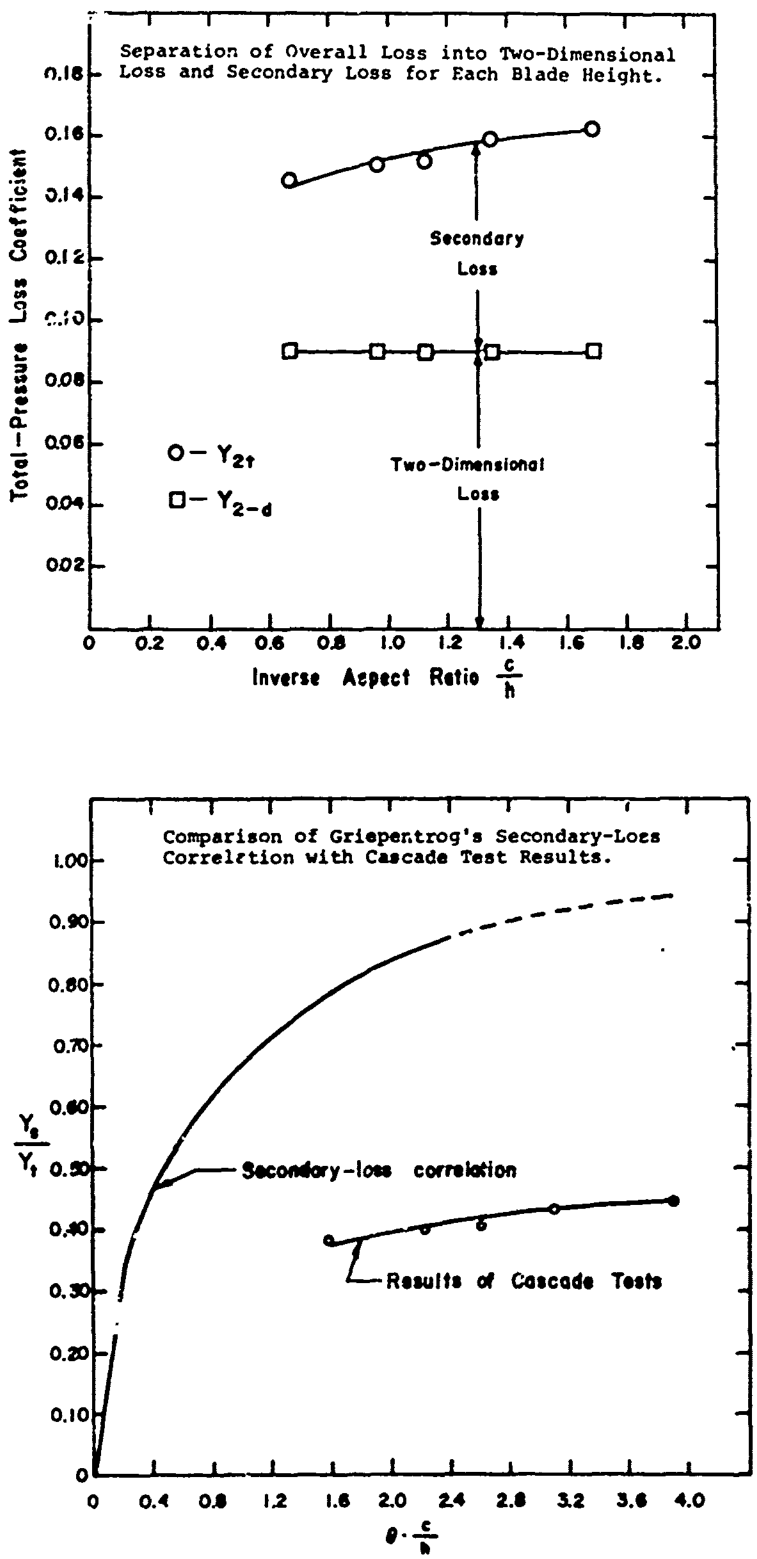


FIGURE 3: Loss Coefficients for a High Turning-Angle Cascade

3. 3-Stage Axial Compressor

The 3-stage compressor was first used by the California Institute of Technology (reference 5). It was then installed at the Turbo-Propulsion Laboratory and preliminary investigations were carried out (references 6 and 7). It is now permanently installed in the Cascade Wind Tunnel building with an improved inlet and throttling arrangement, and with a new drive motor and pulley system to provide a range of operating speeds. The new installation, pictured in figure 4, is reported in reference 8. Results of preliminary measurements (reference 7) are shown in figure 5.

The compressor was designed as a research machine. It has adjustable and replaceable blades so that any row of stator or rotor blades can be totally removed, and the remaining blades can be set to any desired angle. The blade passage has an outer diameter of 36 inches and an inner diameter of 21.6 inches. Many ports are provided in the casing for the insertion of survey probes to traverse in both radial and peripheral directions, before, after, and between stages. Both pressure probes and hot-wire probes are used. Instrumentation includes manometers and micromanometers, and a new automatic data logging system capable of accurately recording many channels of small differential pressures, is being considered.

FIGURE 4: View of the 3-Stage Research Compressor

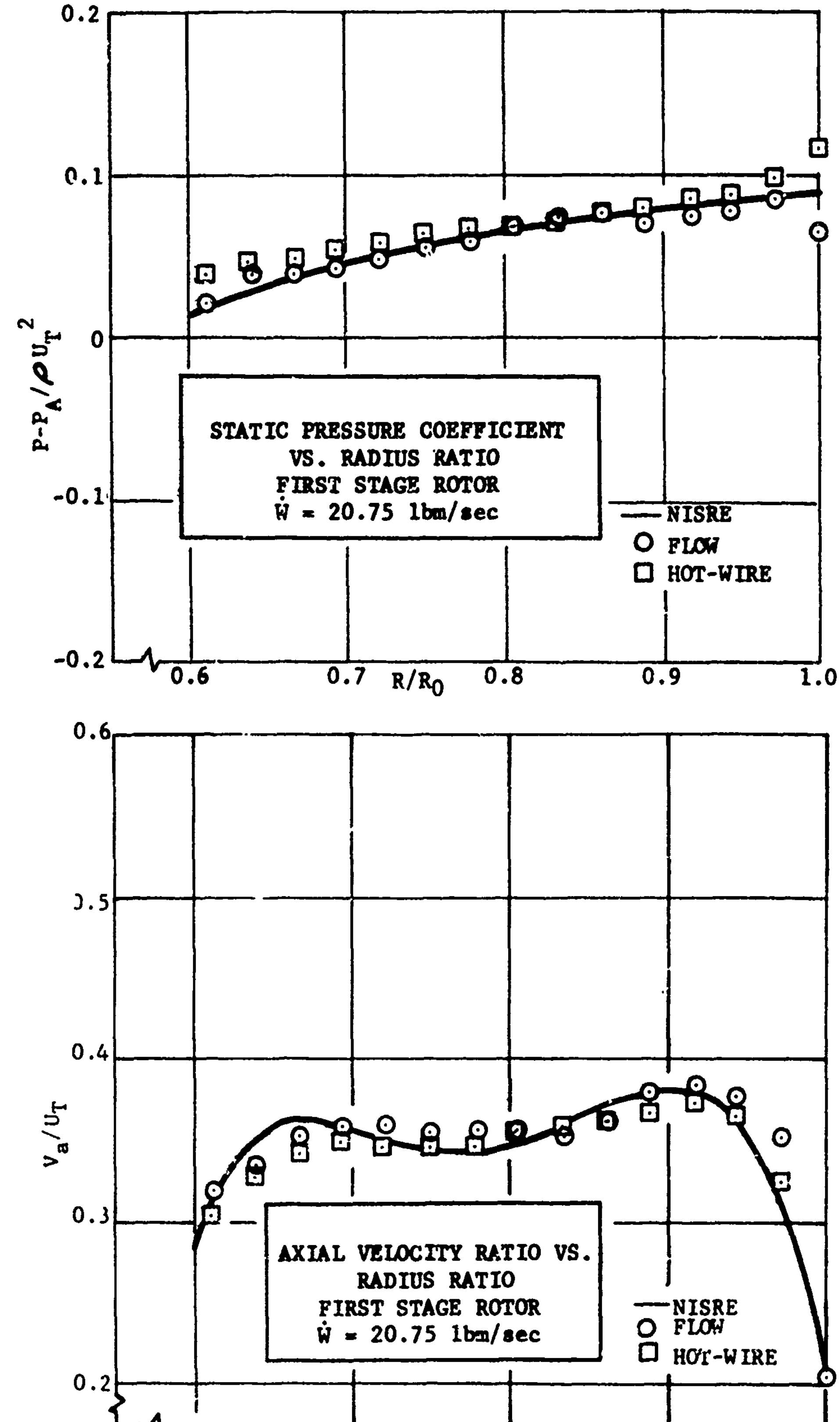


FIGURE 5: Static Pressure Coefficient and Axial Velocity Measured After the First Stage Rotor of the 3-Stage Axial Compressor

4. High Speed Turbine and Compressor Laboratory

This laboratory consists of three test cells, a control and instrumentation room, and a compressor room containing a single 12-stage axial air compressor that provides the power for all experiments. There is also a "spin pit" for the determination of stresses in rotors. A plan of the laboratory is shown in figure 6. Each section will be described separately.

4.1. The Compressed Air Power Supply

Compressed air at up to 11 lbs. per sec. at three atmospheres pressure is supplied to each cell from an Allis-Chalmers multi-stage axial compressor. A schematic of the compressor and supply system is shown in figure 7, and a view of the compressor room is shown in figure 8.

The 1250 H. P. compressor has a variable speed drive with an automatic control and a by-pass surge suppression device. The mass flow rate from the compressor is metered by a sharp edged orifice meter located downstream of an aftercooler in the outlet pipe. The mass flow measurement is described in reference 9 and the performance map of the compressor is given in reference 10.

4.2. Instrumentation and Controls

Experiments carried out in the test cells are controlled by an operator at a central console. The console is on an elevated platform from which the operator can see through small windows into each of two explosion-proof test cells. Access to a third cell that is not explosion-proof is by way of a door. A view of the control area is shown in figure 9.

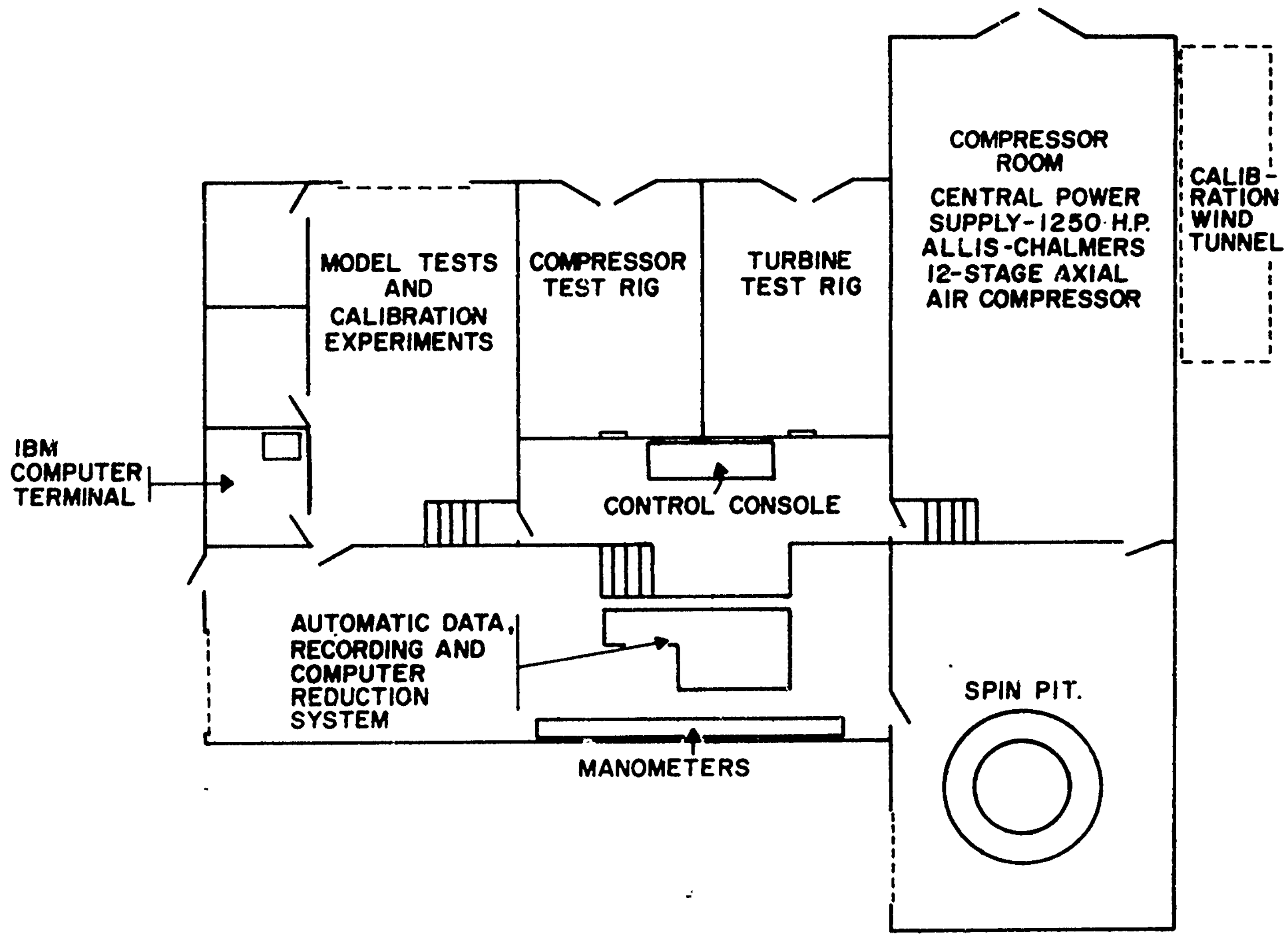


FIGURE 6: Plan of the High-Speed Turbine and Compressor Laboratory

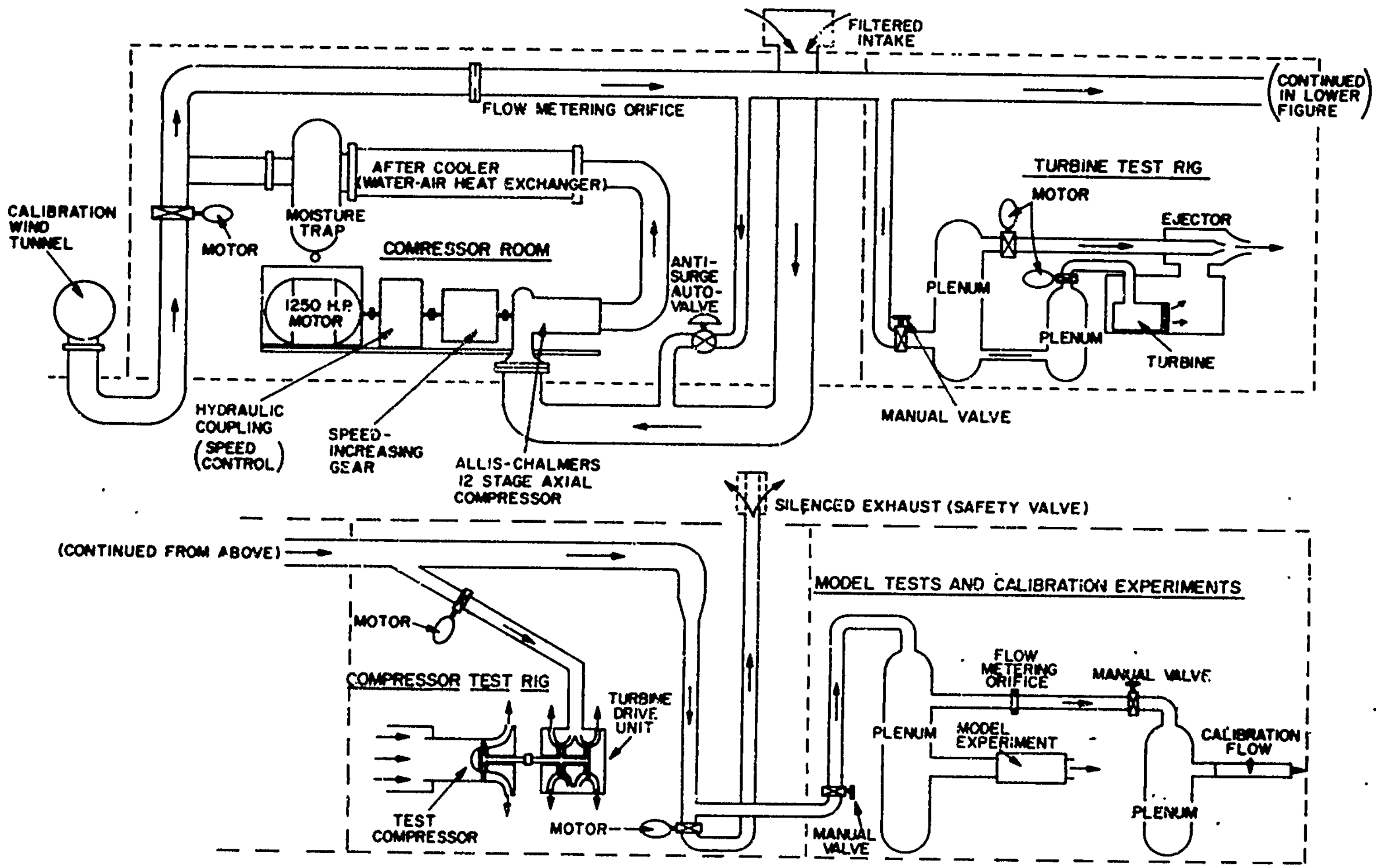


FIGURE 7: Compressed Air Supply System for the High-Speed Turbine and Compressor Laboratory

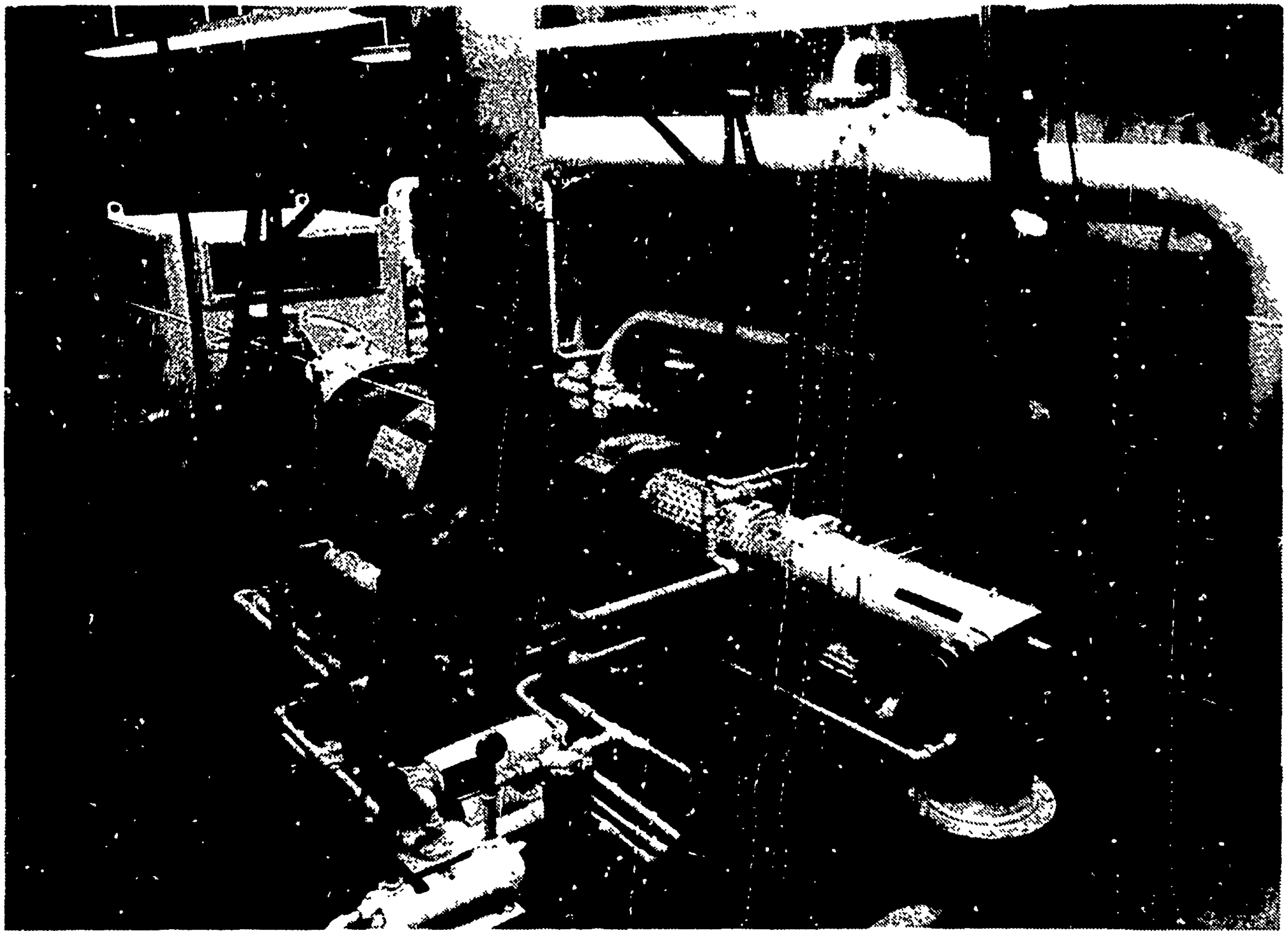


FIGURE 8: View of the Compressor Room in the High-Speed Turbine and Compressor Laboratory

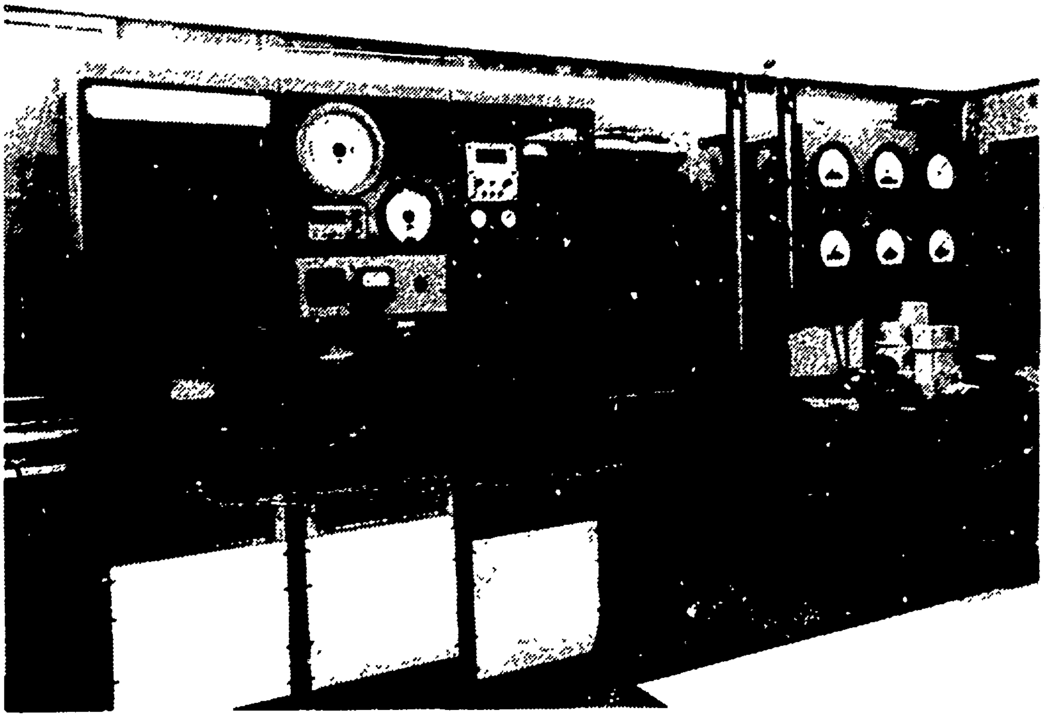


FIGURE 9: View of the Control Area in the High-Speed Turbine and Compressor Laboratory

FIGURE 10: View of the Data Receiving Area in the High-Speed Turbine and Compressor Laboratory

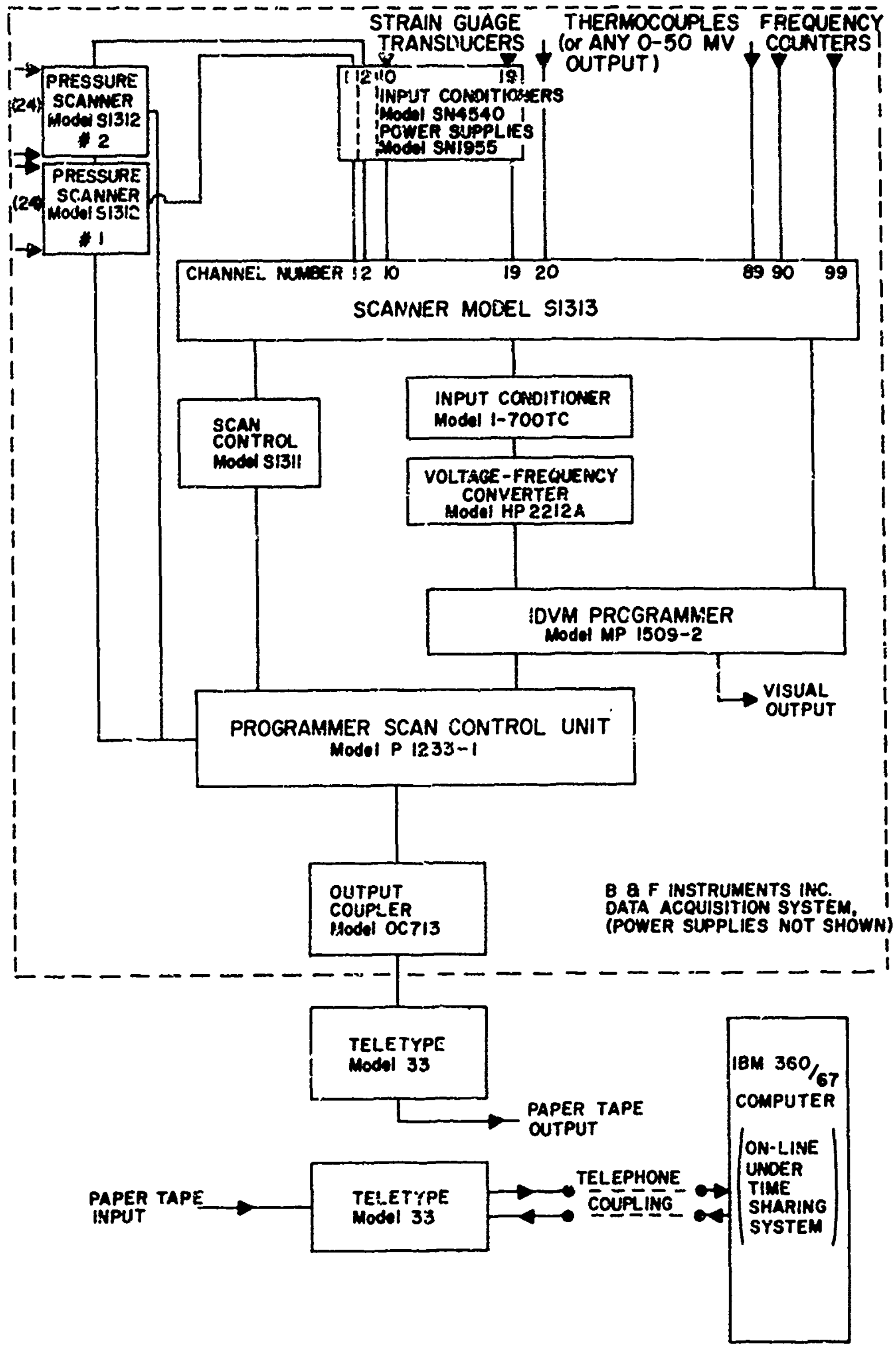


FIGURE 11: Schematic of the Data System in the High-Speed Turbine and Compressor Laboratory

Instrumentation leads, both pressure tubing and electrical leads, from the test cells are brought to the area adjacent to the control platform which contains a data logging and recording system and also four 120-inch, 50-tube manometers and six 120-inch U-tube manometers. A view of this area, which is the data-handling center of this laboratory, is shown in figure 10. The manometers provide a visual display of pressures and distributions of pressure and an on-line check of the pressures that are printed out by the data system.

Pressures, temperatures, frequencies, and strains are scanned, displayed, and recorded by a B & F Model SY 133 solid state data acquisition system. The data, identified by channel number, is printed out and punched onto paper tape by a Model 33 teletype unit. Up to 100 channels can be selected. Channels 1 and 2 are for scanivalves with 24 ports each through which the system scans in turn. Channels 90 to 100 are for frequency counts, and the remainder can be used for thermocouples, strain gauges, and other transducers.

A second teletype unit, Model 33, is coupled by telephone to an IBM 360 which is located on the campus of the Naval Postgraduate School. On-line recording and data deduction is obtained by inputing the punched paper tape after calling for a pre-stored program. The output from the program can be printed on the teletype unit, off-line printed at the terminal or punched onto cards at the terminal. The immediate data reduction and printout allows decisions to be made that affect the course of the test and provides an immediate indication of the presence of experimental errors that might otherwise result in a costly waste of time.

4.3. Turbine Test Rig.

The turbine test rig is designed to measure the intra-stage performance of single stage turbines. One unique feature is that the stator assembly is free to move axially and circumferentially against force capsules so that stator torque and axial force are measured directly. A diagram of the turbine test rig is shown in figure 12. Details of the apparatus and improvements that have been made are given in references 11 to 15. Air supplied from the Allis-Chalmers compressor enters that floating armature, to which the stator is attached, radially from a plenum which is instrumented with total temperature and pressure probes. Labyrinth seals with 0.005 inch radial clearance limit the leakage flow to about .7% of the turbine flow rate. Static pressure taps are provided throughout the gas passage which supply information from which components of the axial force are calculated. The axial force on the closure plate is measured separately by strain gauges mounted on flexures. The turbine torque is measured by an air dynamometer capable of absorbing 200 H. P. at 20,000 r.p.m. Transonic turbines can be tested and pressure ratios of 6 to 1 are achieved using an air-ejector (reference 16) to evacuate the apparatus.

The turbine test rig can be used to evaluate separately the performance of rotor and stator wheels up to 9.7 inches in diameter. The cited referenees describe several types that have been investigated while the test rig itself has been progressively improved. Effects of tip clearance and of rotor-stator spacing have been investigated for particular wheels, and detailed surveys of the flow using pressure probes and hot-wire anemometers have been made in order to compare predicted with measured behavior (reference 15). Investigations of loss coefficients

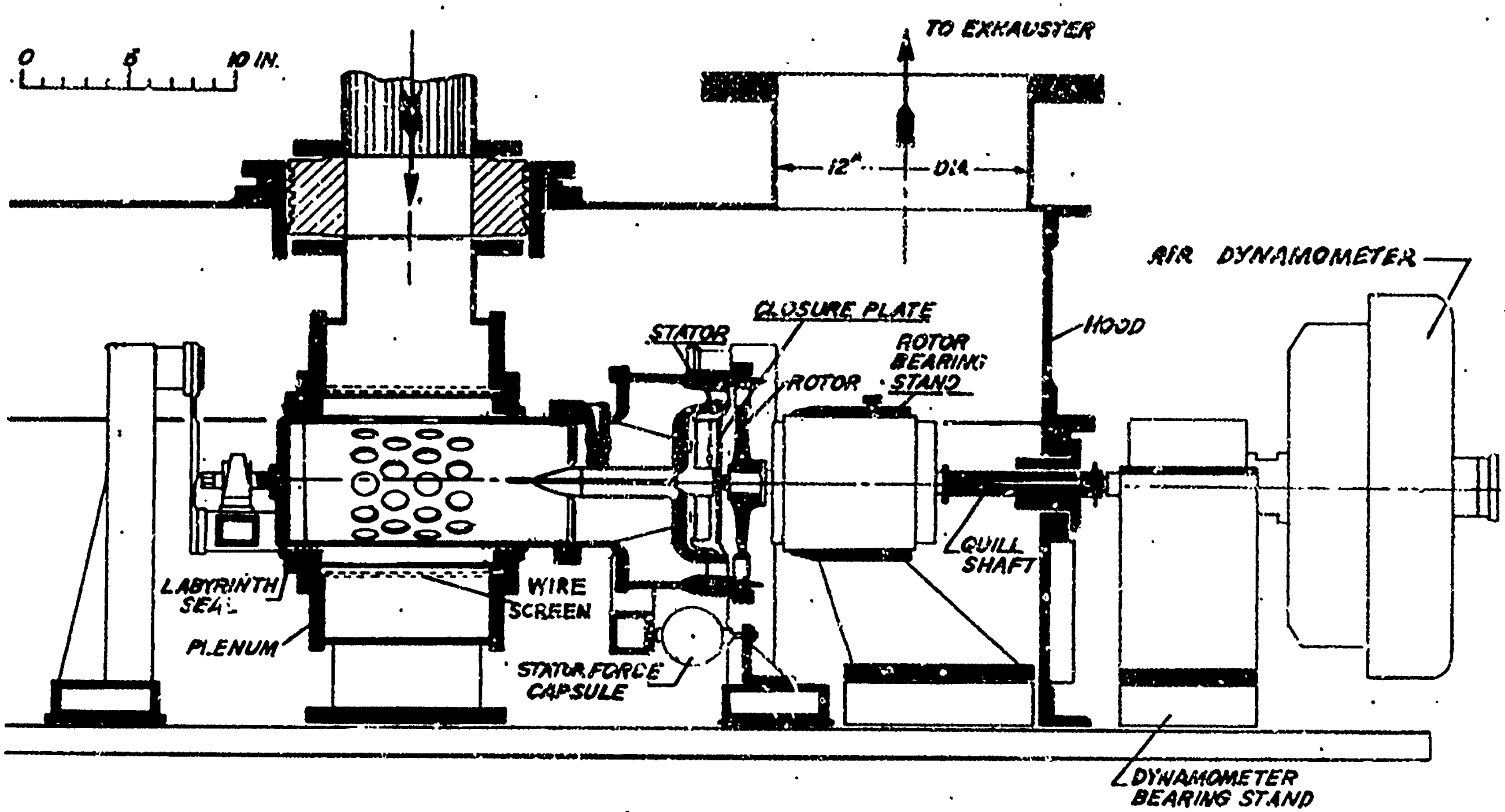


FIGURE 12: The Turbine Test Rig

have been made for turbine blading that has been studied concurrently in the Cascade Wind Tunnel. Figure 13 shows a view of the wheel used on the Turbine Test Rig that corresponds to the blading used by Woods in his study of secondary flows in cascades (reference 4). Figure 14 shows some preliminary results obtained by DeThomas (reference 14) that are related to the results shown in figure 3. The investigation of losses in high-turning-angle cascades and in rotors is a continuing one.

4.4. Compressor Test Rig

Recently completed in the second test cell, the compressor test rig consists of an air-turbine drive unit and an induction pipe containing a throttle, settling chamber, and a flow metering orifice. Any small compressor that matches the available power from the turbine in principle can be installed. The turbine is designed to supply 450 H.P. at close to 30,000 r.p.m. This level of power is required for a transonic compressor, now under construction, that operates with a relative tip Mach number of 1.5. This compressor is a single stage, rotor-stator combination which will provide a means of experimentally determining the flow in a high performance transonic stage (for which there is no completely satisfactory method of design). In addition to hot-wire measurements and the determination of time varying wall pressures, provision is made for holographic interferometry to measure instantaneous density contours. A clear plexiglass casing replaces the steel casing for these measurements.

The first compressor installed in the compressor test rig is the so-called "Hybrid" compressor. This is an experimental machine in which the flow is turned from axial to radial and back to axial inside the rotor. Stator blades are located in a straight annular passage surrounding the inlet duct. A view of the compressor test rig is shown in figure 15 and a view of the Hybrid Compressor installed in the test rig is shown in figure 16.

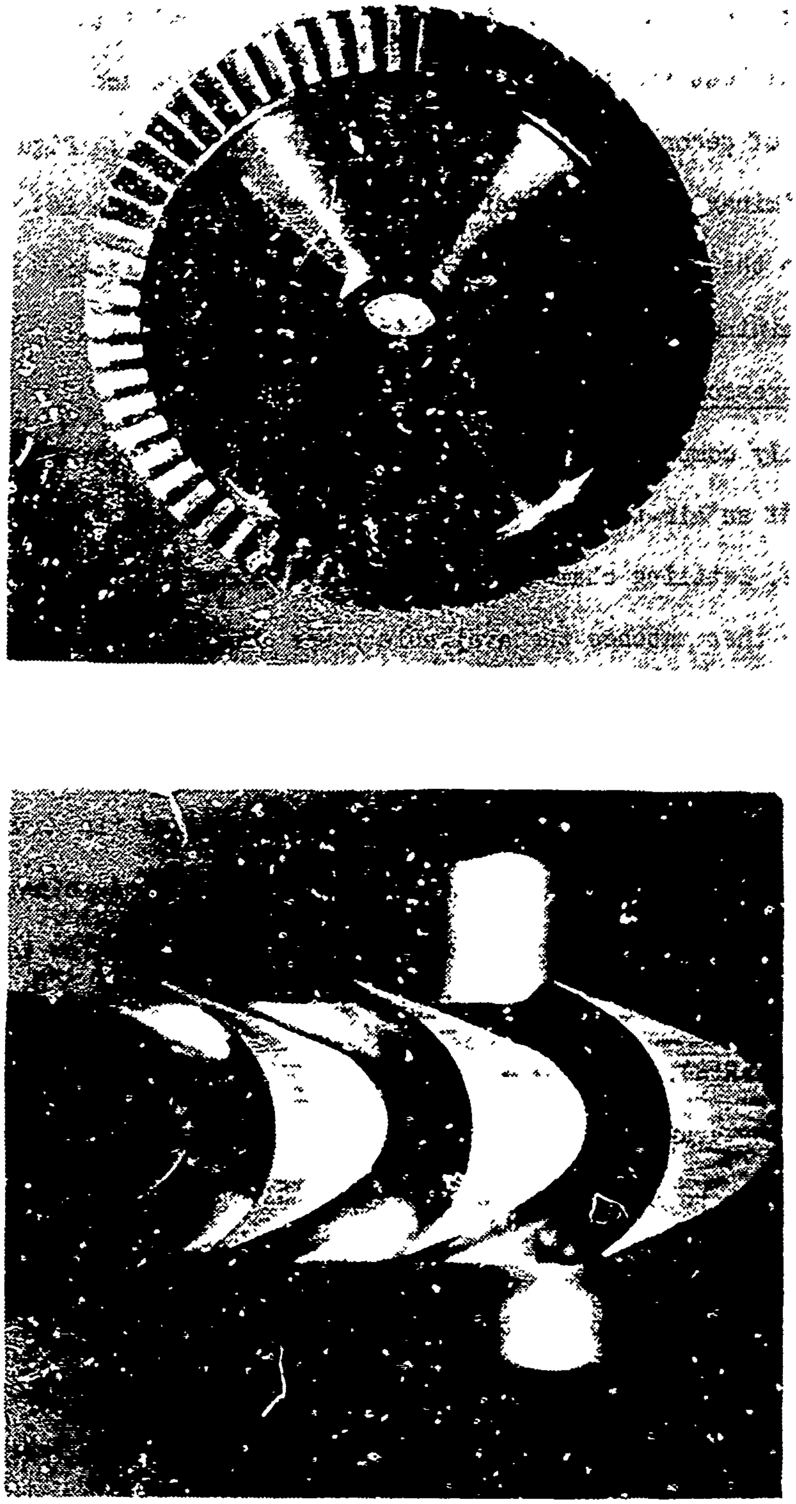


FIGURE 13: Views of a Rotor from the Turbine Test Rig

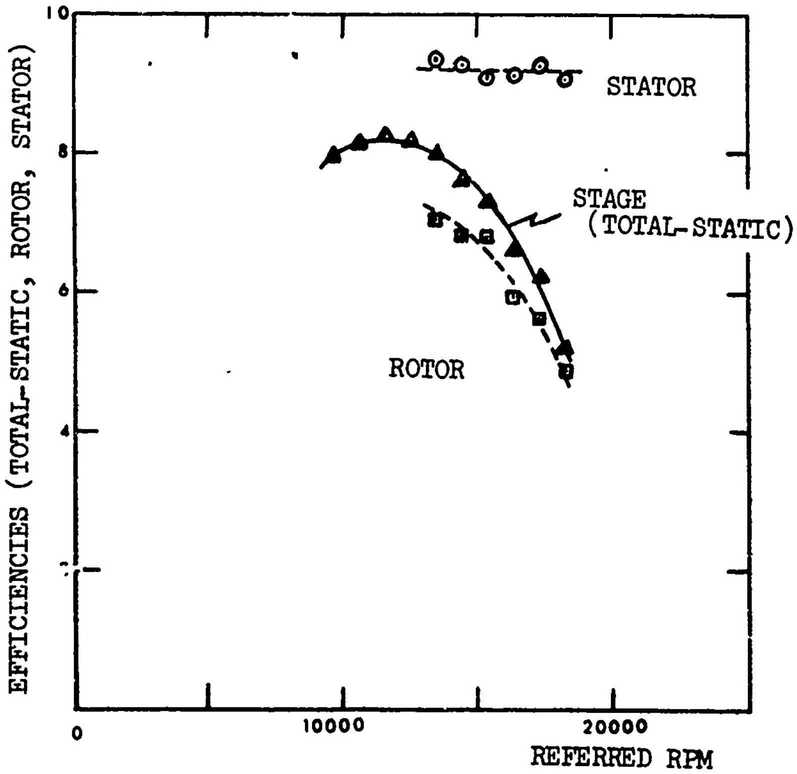


FIGURE 14: Intrastage Efficiencies Measured in the Turbine Test Rig

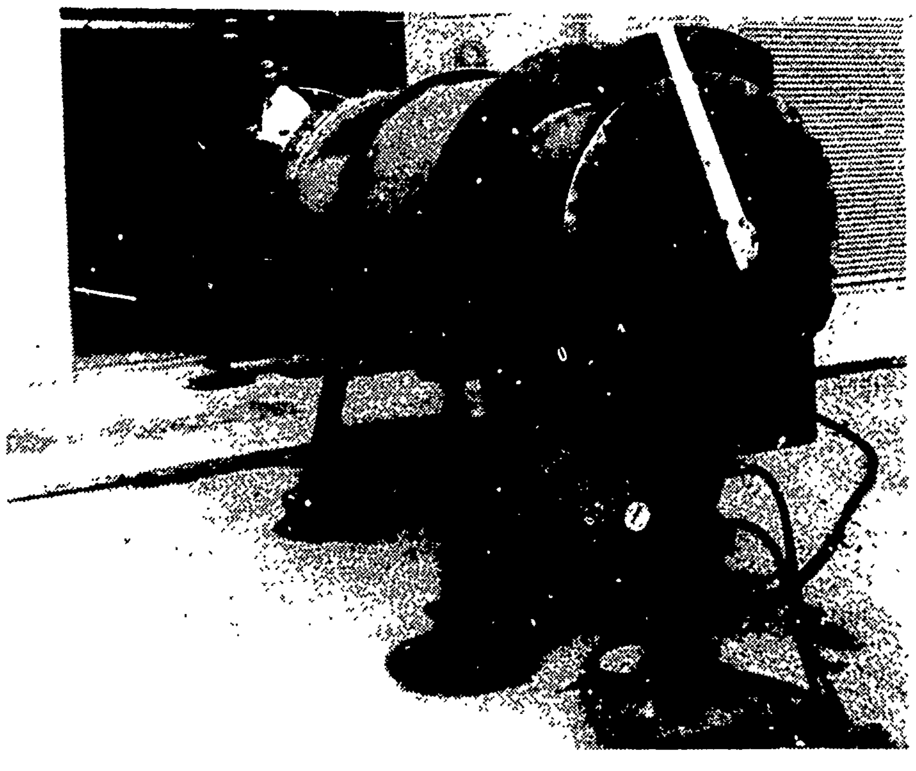


FIGURE 15: View of the Compressor Test Rig

FIGURE 16: Installation of the Hybrid Compressor in the Compressor Test Rig

The compressor test rig has the advantage of providing redundancy in measurements. The operating power can be determined in three ways; either from the mass flow rate and temperature drop through the turbine, or from the mass flow rate and temperature increase through the compressor, or from the speed and the torque measured by strain gauges on flexures between the turbine and compressor stator.

Initial tests of the Hybrid Compressor have been directed at establishing the overall performance of the machine with the adjustable stator blades at their design angle. Using the Data System (Section 3.2) on-line to the IBM-360, computed performance parameters are punched out at the terminal. A plotting program is then used to produce final performance plots as is shown for example in figure 17. The figure illustrates the advantage of redundancy in the measurements. The lower curve disagrees with the other two methods of measuring horsepower because of an interference that was present in the torque measuring system.

Further tests will involve adjustment of the stator blade angles and an axial movement of the stator itself. The proper design of a stator to accept the periodic three-dimensional flow from the rotor is one challenge this machine provides. To determine the time varying flow leaving the rotor is an experimental challenge similar to that presented by the transonic compressor, which will follow the Hybrid into the compressor test rig.

4.5. Model Tests and Calibration Experiments

The third test cell is equipped with two large settling chambers into each of which the air from the Allis-Chalmers compressor can be fed by an adjustment of valves. Steady flow experiments can be mounted on

the outlet bellmouths of these chambers and some examples of these will be given. A view of the test cell is shown in figure 18.

(i) Calibration of Flow Probes in Uniform Flow

Throughout the Turbopropulsion Laboratory two-dimensional and three-dimensional directional pressure probes are used to determine distributions of velocity. Calibration of these probes is generally required for effects of Mach number, yaw and, for the three-dimensional probe, pitch. These calibrations are carried out in a round pipe, 6 feet long and 10 inches in diameter attached to one of the settling chambers. A Prandtl pitot-static probe is mounted in the 10 inch pipe at the measurement station and pressure differences are measured on two banks of four 120 inch water U-tube manometers.

(ii) Calibration of Flow Probes in Uniform-Shear Flow

From student laboratory projects, two methods of generating axial flows with nearly uniform shear profiles are available. They are illustrated in Figure 19. Examples of velocity profiles obtained with the divided-duct apparatus, and preliminary results for the error in the flow angle indicated by two different probes are given in figure 20.

(iii) Flow in a Rectangular Duct Bend

Some features of secondary flows in high turning cascades are also developed in curved ducts. A 5 inch by 5 inch plexiglass and aluminum duct has been built in straight and curved sections, so that bends up to 135° with a 1 foot inner radius, and equivalent straight ducts can be measured in turn. A force plate has been used to measure exit momentum and the results were found to compare favorably with an integration of exit probe surveys. (References 4 and 17)

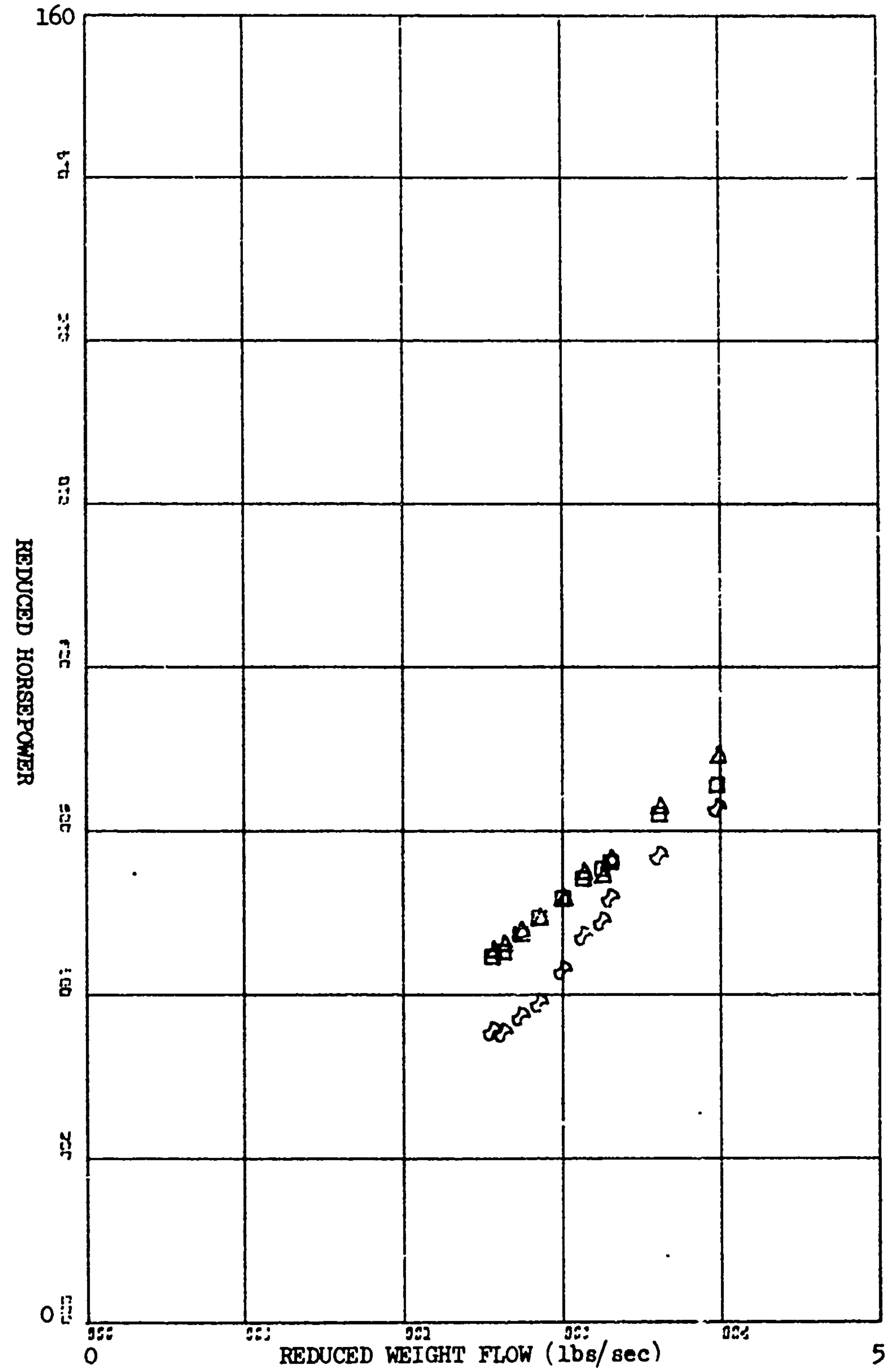


FIGURE 17: Computer-Plotted Performance of the Hybrid Compressor. (Δ - H.P. from turbine flow measurements; □ - H.P. from compressor flow measurements; ∞ - H.P. from torque and R.P.M.)

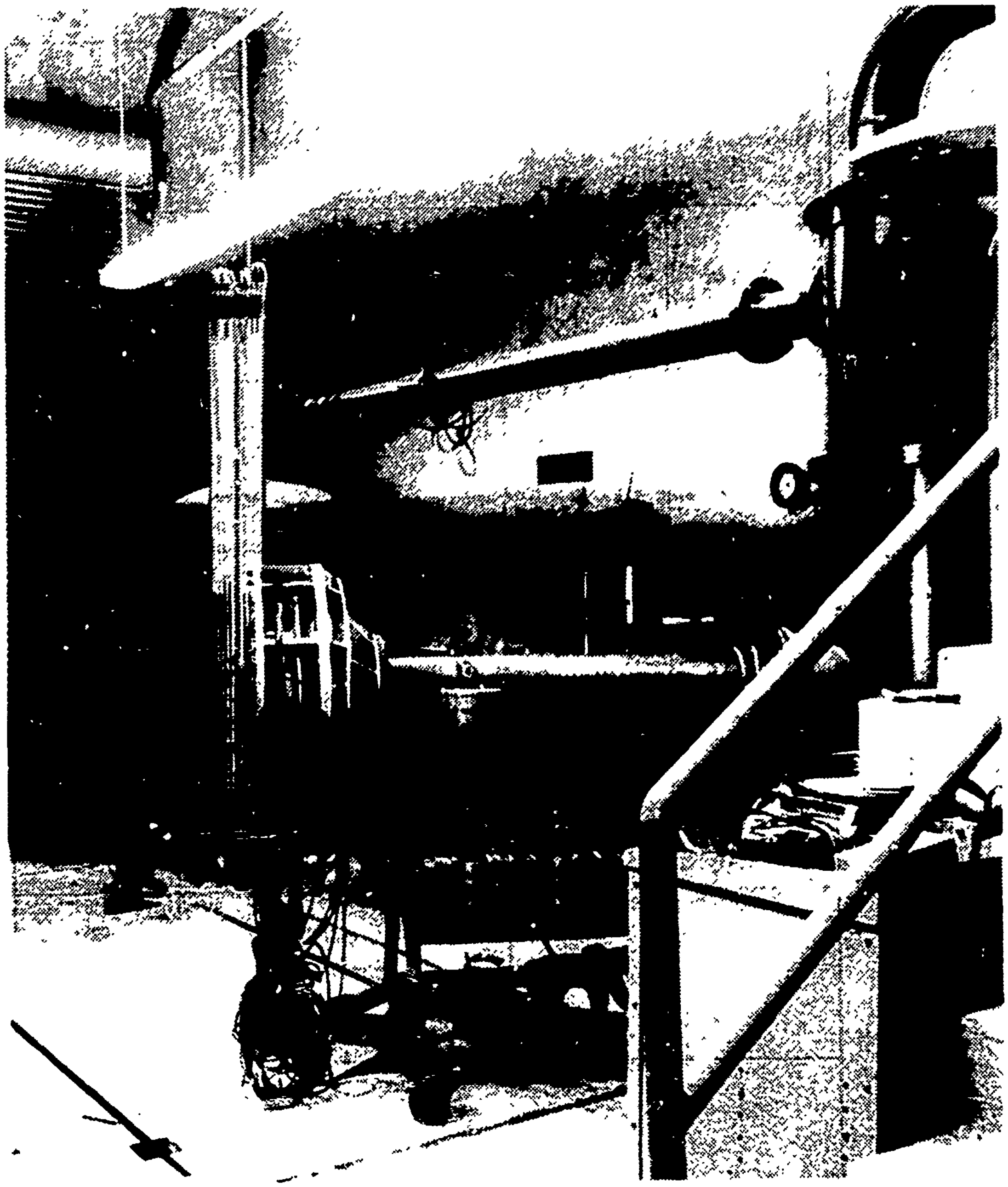


FIGURE 18: View of the Test Cell for Model Tests and Calibration Experiments

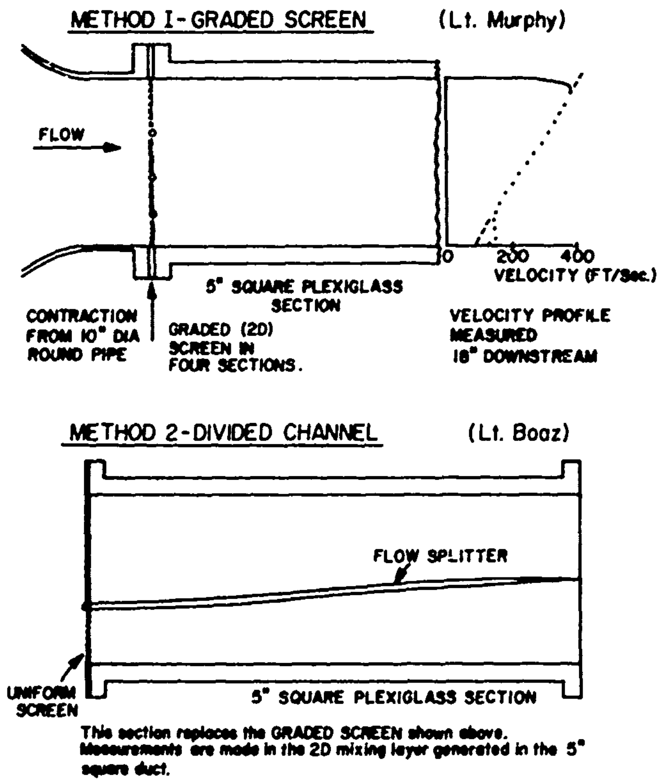


FIGURE 19: Apparatus for the Generation of Uniform Shear Flows

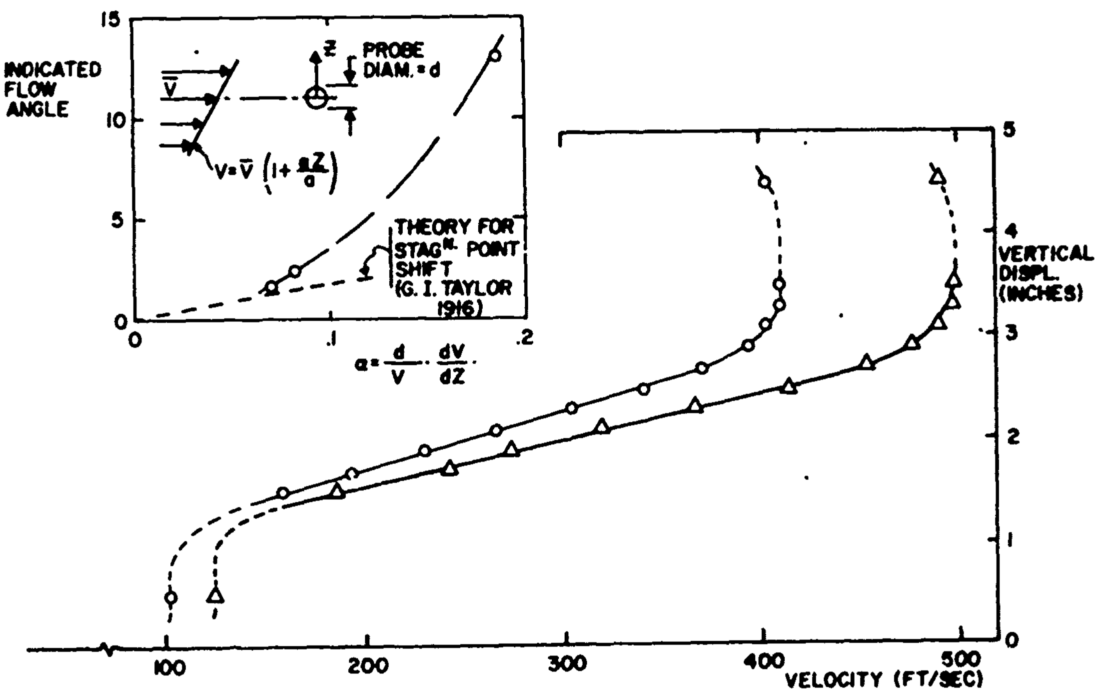


FIGURE 20: Preliminary Results for Probe Angle-Error in Uniform Shear Flow

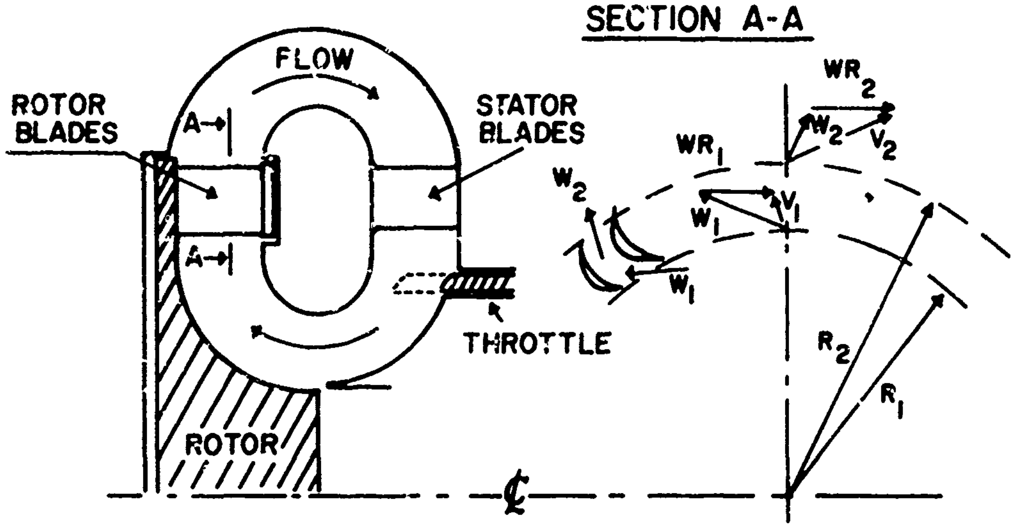
(iv) Energy Absorber Model

Analysis of a turbohydraulic energy absorber for the arrest of aircraft on carriers which would replace the presently used piston type, produced the prediction that the more aerodynamically efficient the components of the device could be made the smaller would be its overall size, and the faster it would rotate (references 18 and 19). A knowledge of the loss coefficients in flow passages and blade arrays with the geometry of the proposed absorber is required in the design calculations. A stationary device in which the relative flow is modeled is used to establish these coefficients. Figure 21 shows the rotary energy absorber with a section of the stationary energy absorber model. A view of the model can be seen in figure 18.

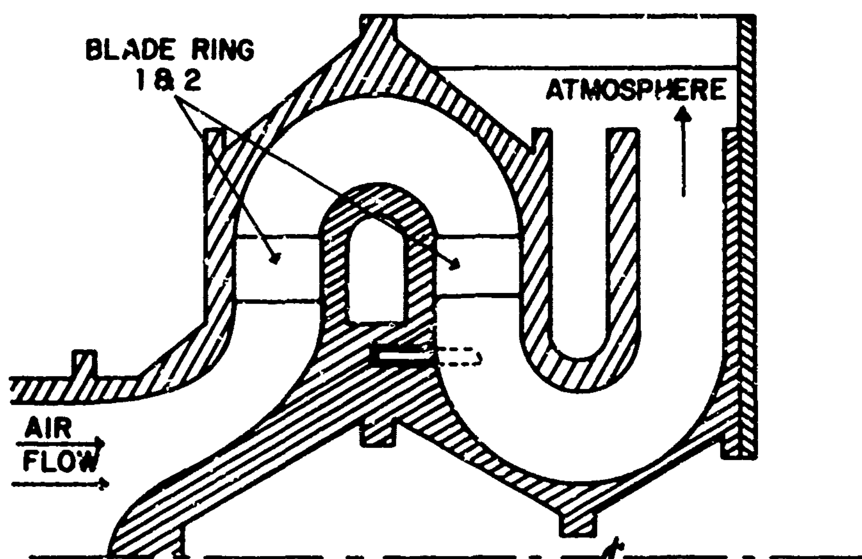
4.6. Spin Pit

The stresses that occur in rotors as a result of centrifugal forces and thermal loading often limit the design of turbomachines. Because of complicated geometries, stresses can not be calculated reliably and a controlled experimental determination of rotor stresses with known centrifugal and thermal loading is desirable. A facility for this purpose is the Spin Pit, which can accommodate rotors up to 50 inches in diameter and 24 inches in length. A diagram showing a rotor installed for testing and an outside view of the facility are shown in figures 22 and 23 respectively.

The test rotor, in a reinforced concrete pit, is spun by an air turbine capable of speeds up to 50,000 r.p.m. The pit can be evacuated to 50 microns pressure to reduce air loads to a minimum. A 30 KVA, 10 KHz motor-generator set is used to heat the rotor disc by induction, and surrounding water-cooled wall surfaces can generate temperature



a) [illegible]MATIC OF A TURBO-HYDRAULIC ENERGY ABSORBER.



b) SCHEMATIC OF THE ENERGY ABSORBER FLOW MODEL.

FIGURE 21: A Rotary Turbo-Hydraulic Energy Absorber and a Relative Flow Model for Measurements with Air

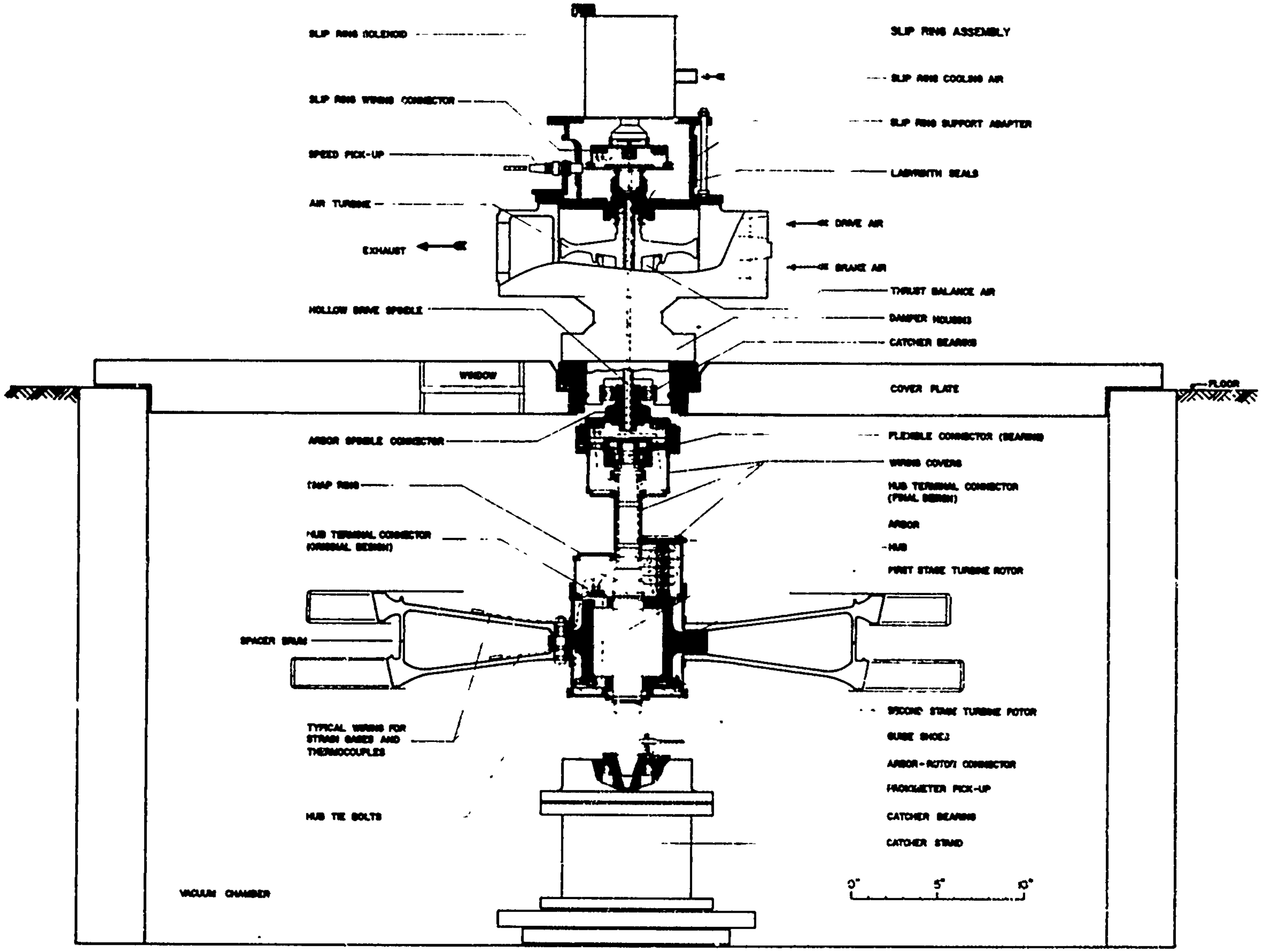


FIGURE 22: Test Rotor in the Spin Pit

FIGURE 23: View of the Spin Pit Facility

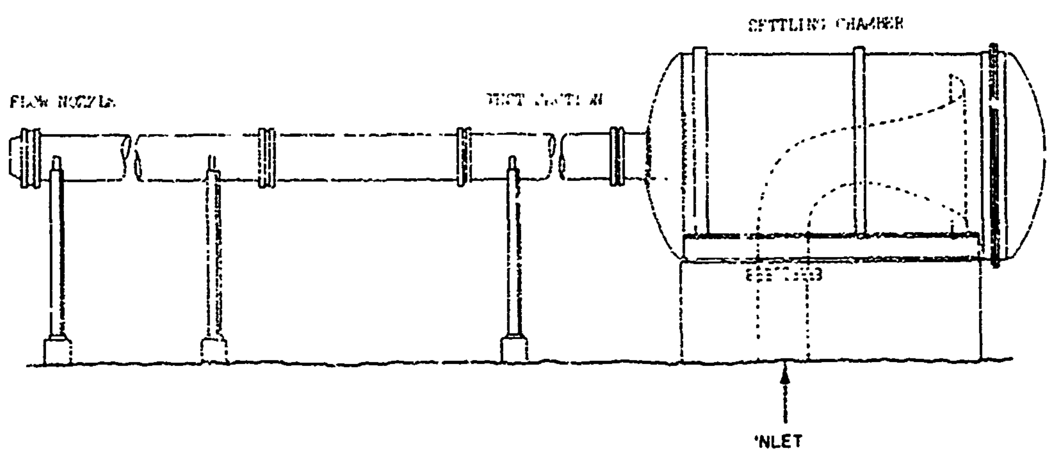


FIGURE 24: Probe Calibration Wind Tunnel

gradients within the structure. Temperatures of 1800°F near the rim and 800°F near the axis are possible. The drive turbine is arranged so that a reversal of the air supply will provide braking. A catcher device is provided in the bottom of the pit to minimize damage in the case of a rupture or shaft separation.

The electrical signals from thermocouples and strain gauges on the test rotor are led out of the pit on a slip ring assembly at the top of the hub. A Lebow 16-channel assembly with continuous brush contact and cooled by liquid freon can be used up to 50,000 r.p.m. A Superior-Carbon 36-channel assembly which uses intermittent brush contact and is air-cooled can be used up to 20,000 r.p.m. The data logging system (Section 4.2) is used to record data. The spin pit has been used to measure rotor stresses in the absence of thermal stresses (reference 20) and also when thermal stresses were present (reference 21). The latter reference contains a full description of the Spin Pit and of the methods used to overcome the difficulties of obtaining reliable strain gauge data from a rotating test specimen.

4.7. Probe Calibration Wind Tunnel

Outside the compressor room is located an annular wind tunnel that is intended for the calibration of pressure and hot-wire probes at velocities from subsonic to supersonic. To date, the apparatus itself has not been calibrated. The test passage is fed from a large settling chamber (figure 24) and is followed by a flow metering orifice discharging to atmosphere.

5. Other Apparatus

Several pieces of apparatus remain from earlier contract and thesis research projects. In some cases the apparatus is suitable for currently important problems, and three examples will be given.

5.1. Intake Test Rig

Intake ducts and diffusers of special design can be investigated in the Cascade Wind Tunnel building. The 750 H.P. Cascade Drive Motor draws air from the room into the test duct which is adapted to one of the cover plates in the floor of the cascade laboratory (see figure 1). The air is exhausted through the doors on the east side of the basement while the doors on the west side are closed. The Cascade Wind Tunnel data system can be used for probe surveys in this rig.

5.2. Radial Inflow Turbine

A radial inflow turbine is located in the third test cell of the high speed turbine and compressor laboratory. In this machine, air enters radially inwards from a tapered scroll surrounding the rotor and passes through guide vanes into a dual-discharge rotor. The rotor inlet is 9.4 inches in diameter, with an exit diameter of 5.88 inches at the tip and 3.52 inches at the hub. A view of the machine is shown in figure 25.

An interesting result obtained with this machine can be seen in figure 26 (reference 22). In a study of the effect of rotor clearance, Riley found that the clearance could be increased with slight penalty until a value was reached beyond which a rapid deterioration occurred.

A separate study was made of the flow in the scroll and inlet guide vanes that demonstrated the interesting phenomena that can occur in a compressible vortex (reference 23).

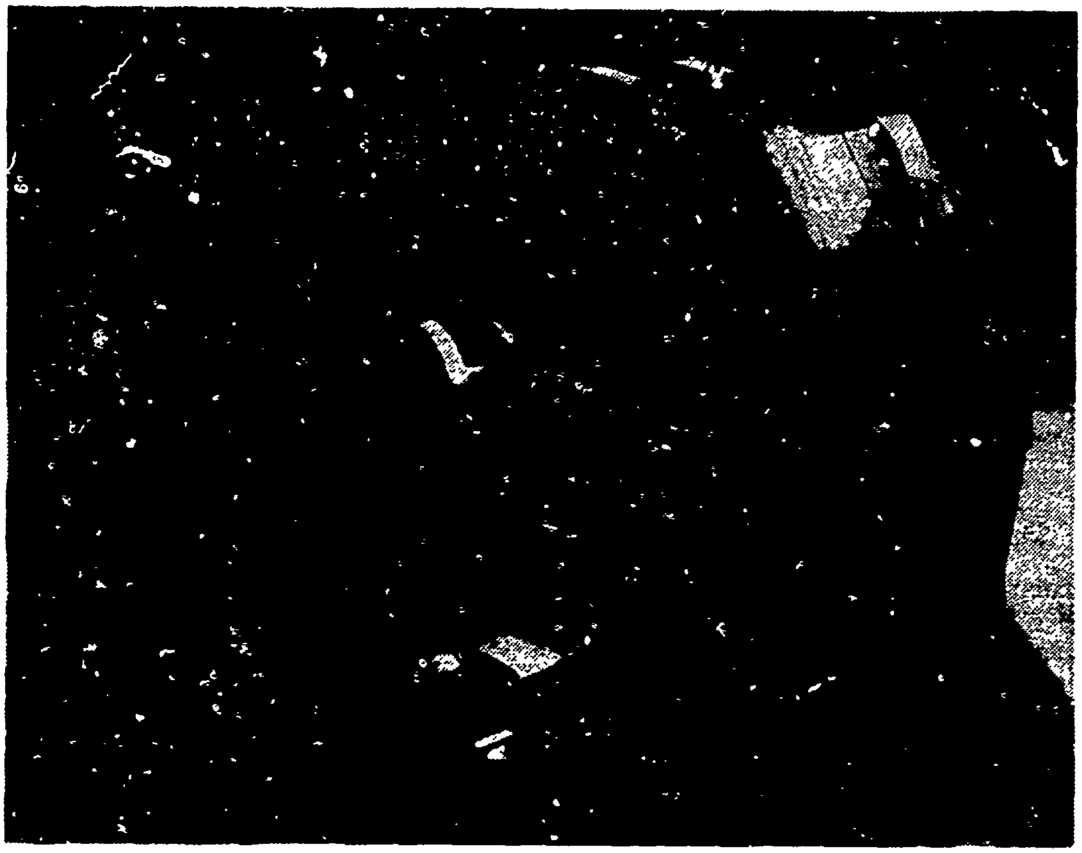


FIGURE 25: View of the Radial-In Flow Turbine

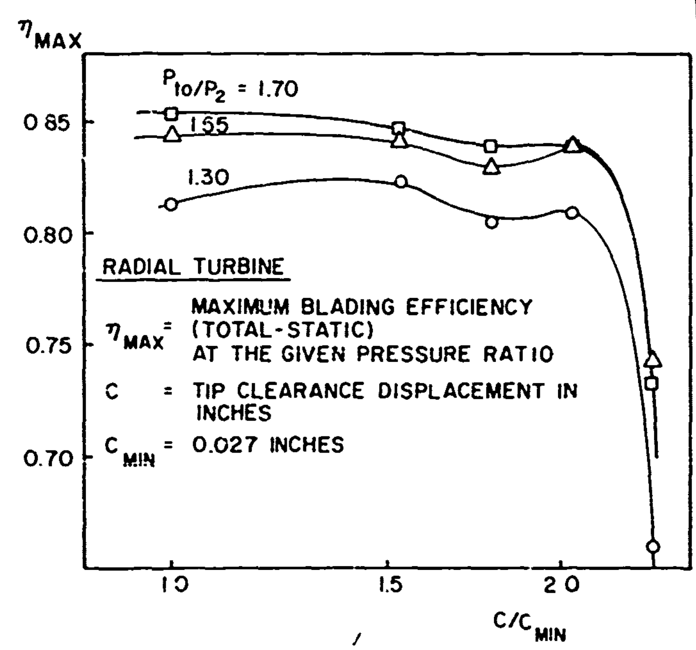


FIGURE 26: Effect of Tip Clearance on the Blading Efficiency of a Radial-In Flow Turbine

5.3. Radial Compressor Rig

One of the earliest research turbomachines built at the Naval Postgraduate School is described fully in reference 24. Some of the results obtained are included in reference 25. It is noted that many of the questions posed as research topics in reference 24 have not been resolved satisfactorily up to the present time, and the Radial Compressor Test Rig remains a potentially useful research tool.

6. Comments

The Turbopropulsion Laboratory has in the past eight years steadily grown in its ability to conduct experimental research toward the development of improved turbomachinery. During this period, the laboratory has provided the environment and the opportunity for more than 30 Naval officers to complete theses toward advanced engineering degrees. The theses themselves were an integral part of the laboratory's growth. Also, the laboratory has regularly provided courses to supplement lectures in turbomachinery and to confront students with the real world of flows in turbomachines.

The capability has been provided to tackle some important research questions in the aerodynamics of turbomachinery. A start has been made (reference 4) toward understanding the development of secondary flows and the associated losses that occur in a cascade of blades. The Cascade Wind Tunnel and the Turbine Test Rig provide the opportunity to continue this work. Tip clearance effects on the performance of compressor stages will be studied using the 3-Stage Research Compressor. The size of this machine allows detailed measurements to be made of the development and properties of the casing boundary layers, so that the more recent boundary layer theories can be evaluated and possibly improved.

The research challenge in high speed compressors is both analytical and experimental. Analytically the key problem is to properly design a transonic cascade, either rotating or stationary, that is not a priori assumed to be two-dimensional. Experimentally the main problem is to determine what is the actual flow in an operating machine that has been designed using specified approximate methods. This requires new experimental approaches. Holography has been proposed but has yet to be demonstrated in the actual machine geometry, and at the high characteristic

frequencies of the flow. Hot wires can not be applied quantitatively without a better understanding of their behavior in steady transonic flows. However, they can possibly be applied to determine flow quality, such as the extent of flow separation and the presence of shock waves.

Clearly a greater effort must now go into improving methods of determining actual flow fields within rotating machines. The Hybrid Compressor and the new Transonic Compressor provide flows of ascending difficulty. The direct attempt to solve the development problems of these machines must automatically result in the development of new techniques with wide application.

In addition to these main research directions, the laboratory will continue to accommodate smaller projects that are derived from new ideas as they occur. The energy absorber is an example of this. Smaller experiments can be attached to either the Allis-Chalmers air supply in the Model Test and Calibration Experiments Test Cell, or to the Cascade Wind Tunnel air supply supply using one of the floor cover plates in the cascade building.

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